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(54) **CONFIGURABLE COMBINATION
SPECTROMETER AND POLARIZER**

(56) **References Cited**

U.S. PATENT DOCUMENTS

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4,934,816 A * 6/1990 Silver G01J 3/02
250/343
5,045,701 A * 9/1991 Goldstein G01J 3/447
250/339.07
5,166,749 A * 11/1992 Curbelo G05B 19/39
318/640
5,253,110 A * 10/1993 Ichihara G02B 27/09
355/53
5,345,306 A * 9/1994 Ichimura G01N 21/17
356/451
5,528,368 A * 6/1996 Lewis G02B 21/33
250/339.02
6,122,023 A * 9/2000 Chen G02F 1/1334
348/E9.026
6,490,043 B1 12/2002 Kebabian
6,961,123 B1 * 11/2005 Wang G01J 4/04
356/364
7,016,040 B2 3/2006 Chen et al.
7,382,498 B1 * 6/2008 Cook G01J 3/02
356/326
7,742,173 B2 * 6/2010 Yun G01N 21/4795
356/479

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G01J 3/06 (2006.01)

FOREIGN PATENT DOCUMENTS

EP 2682741 A1 1/2014

OTHER PUBLICATIONS

Thériault, Jean-Marc et al., "A New Imaging FTS for LWIR Polarization Sensing: Principle and Application", Imaging and Applied Optics Technical Digest, 2011.

(Continued)

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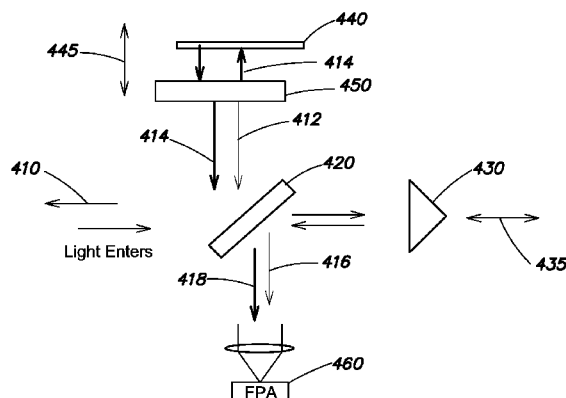
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(57) **ABSTRACT**

A multimode configurable imaging spectropolarimeter in which the polarimetry function can be activated and deactivated on demand.

17 Claims, 8 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

7,797,119	B2 *	9/2010	de Boer	.....	A61B 5/0059	702/69
8,130,378	B2 *	3/2012	Wu	.....	G01N 21/21	356/364
8,203,715	B2	6/2012	Robinson	.....	
8,334,982	B2 *	12/2012	Fang-Yen	.....	G01N 21/45	356/497
8,705,046	B2 *	4/2014	Yun	.....	A61B 5/0059	356/479
9,086,264	B2 *	7/2015	Wang	.....	G01N 21/4795	
2004/0104359	A1 *	6/2004	Komatsuda	.....	G03F 7/70075	250/492.2
2005/0283058	A1 *	12/2005	Choo-Smith	.....	A61B 5/0088	600/315
2007/0038040	A1 *	2/2007	Cense	.....	A61B 3/1005	600/310
2007/0109553	A1 *	5/2007	Feldchtein	.....	A61B 5/0066	356/492
2007/0146720	A1 *	6/2007	Cox	.....	G01J 3/2823	356/451
2007/0165234	A1 *	7/2007	Podoleanu	.....	A61B 3/102	356/451
2008/0043244	A1 *	2/2008	Hatori	.....	G01B 9/02004	356/479
2008/0117431	A1 *	5/2008	Teramura	.....	G01B 9/02004	356/511
2008/0285043	A1 *	11/2008	Fercher	.....	A61B 3/102	356/451
2010/0002241	A1 *	1/2010	Hirose	.....	A61B 3/102	356/497
2010/0018289	A1	1/2010	Oda	.....	
2010/0141954	A1 *	6/2010	Kobayashi	.....	G01B 9/02007	356/479
2010/0149533	A1 *	6/2010	Fest	.....	G01J 4/00	356/367
2010/0166293	A1 *	7/2010	Sugita	.....	A61B 3/102	382/154
2010/0290053	A1 *	11/2010	Robinson	.....	G01J 3/02	356/451
2011/0228222	A1 *	9/2011	Kobayashi	.....	A61B 3/102	351/206
2011/0255095	A1 *	10/2011	Jiang	.....	G01B 9/02004	356/479
2011/0267340	A1 *	11/2011	Kraus	.....	A61B 3/102	345/419
2011/0273668	A1 *	11/2011	Hirose	.....	A61B 3/102	351/206
2012/0200859	A1 *	8/2012	Breitenstein	.....	A61B 3/102	356/479
2013/0003077	A1 *	1/2013	Suehira	.....	A61B 3/102	356/479
2013/0107277	A1 *	5/2013	Hirose	.....	A61B 3/102	356/512
2013/0301006	A1 *	11/2013	Kim	.....	A61B 3/102	351/206
2013/0338510	A1 *	12/2013	Tearney	.....	A61B 5/0066	600/478
2014/0078298	A1 *	3/2014	Kudenov	.....	G01J 3/2803	348/135
2014/0176963	A1 *	6/2014	Kemp	.....	G01B 9/02004	356/497
2014/0192364	A1 *	7/2014	Yatagai	.....	A61B 3/102	356/491
2015/0168210	A1 *	6/2015	Dorschner	.....	G01J 1/0429	349/18

OTHER PUBLICATIONS

U.S. Appl. No. 13/450,371, titled "Infrared Spectrometer with Enhanced Readout Speed," filed Apr. 18, 2012.
 Vandervlugt, Corrie et al., "Ground Vehicle Spectral and Polarization Imaging Sensor", College of Optical Sciences.
 Dignam et al., "Analysis of a Polarizing Michelson Interferometer for Dual Beam Fourier Transform Infrared, Circular Dichroism Infrared, and Reflectance Ellipsometric Infrared Spectroscopies", Applied Spectroscopy, The Society for Applied Spectroscopy, Baltimore, US, vol. 35, No. 2, Mar. 1, 1981, pp. 186-193.
 Goldstein et al., "Infrared Spectropolarimetry", Optical Engineering, Soc. of Photo-Optical Instrumentation Engineers, Bellingham, vol. 28, No. 2, Feb. 1, 1989, pp. 121-122.

* cited by examiner

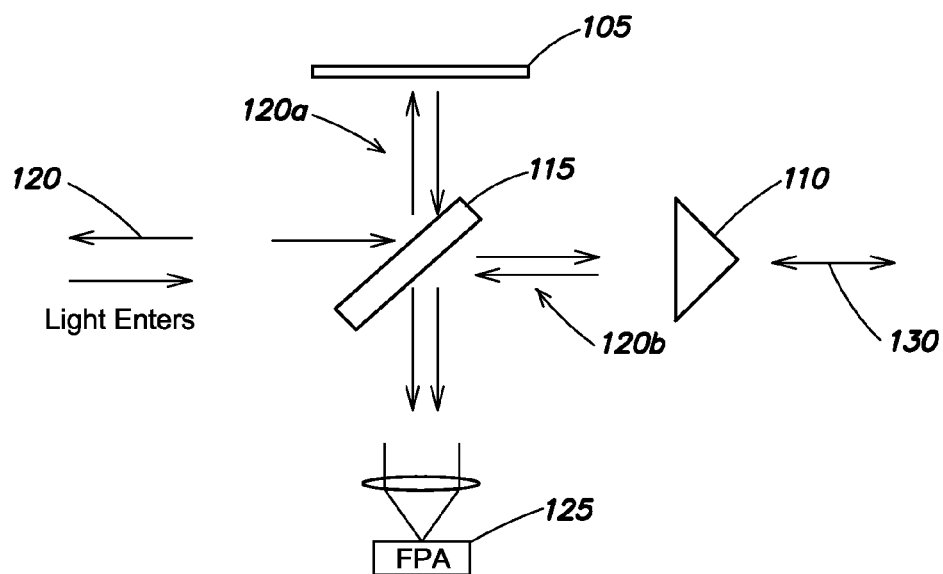


FIG. 1A

(Related Art)

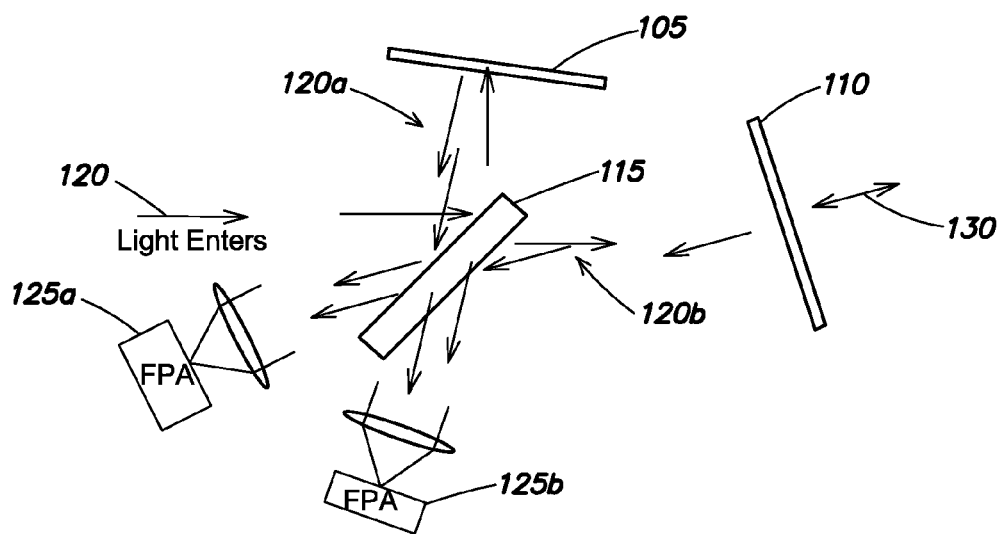


FIG. 1B

(Related Art)

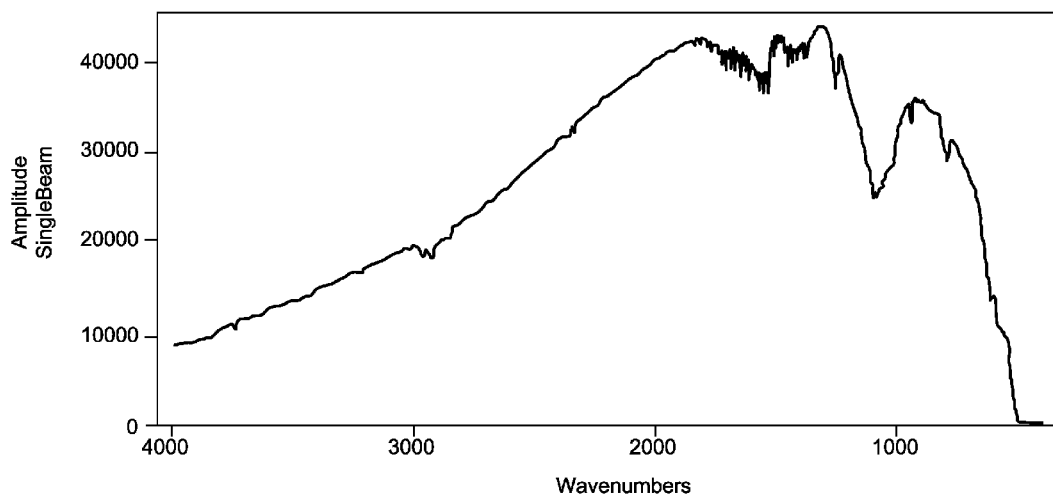


FIG. 2
(Related Art)

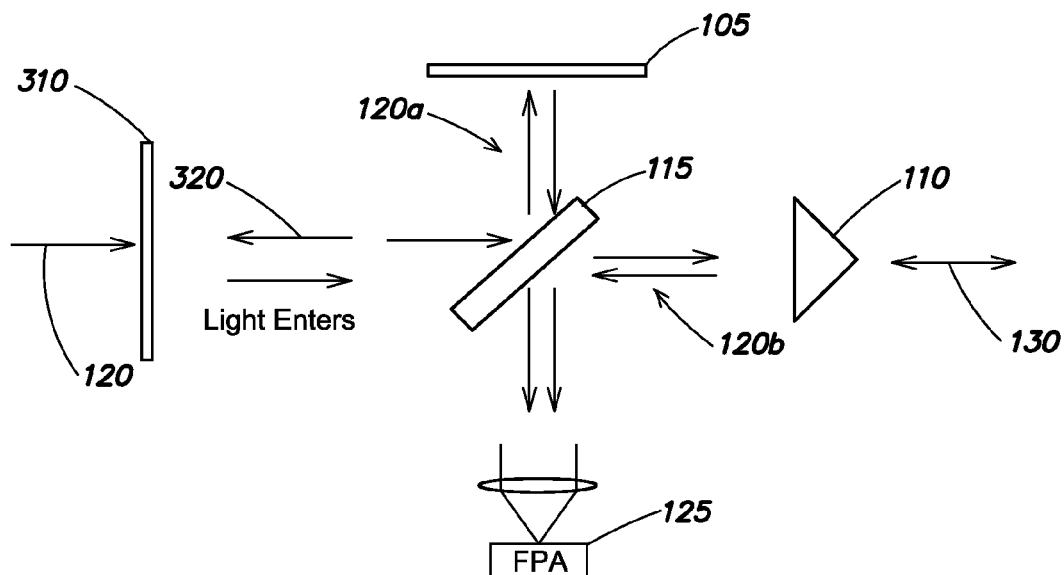


FIG. 3
(Related Art)

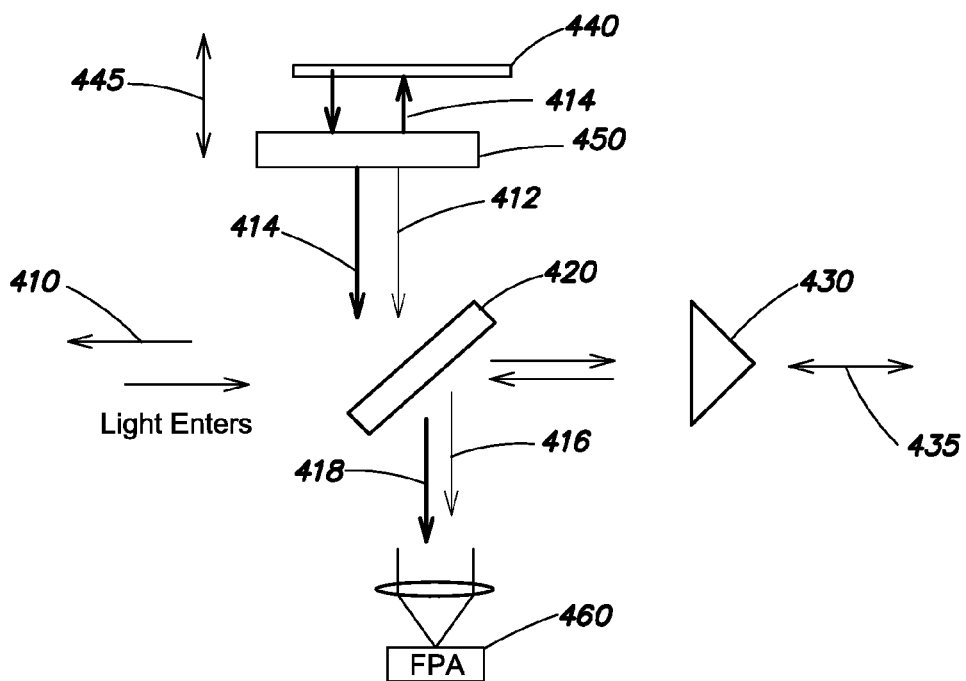
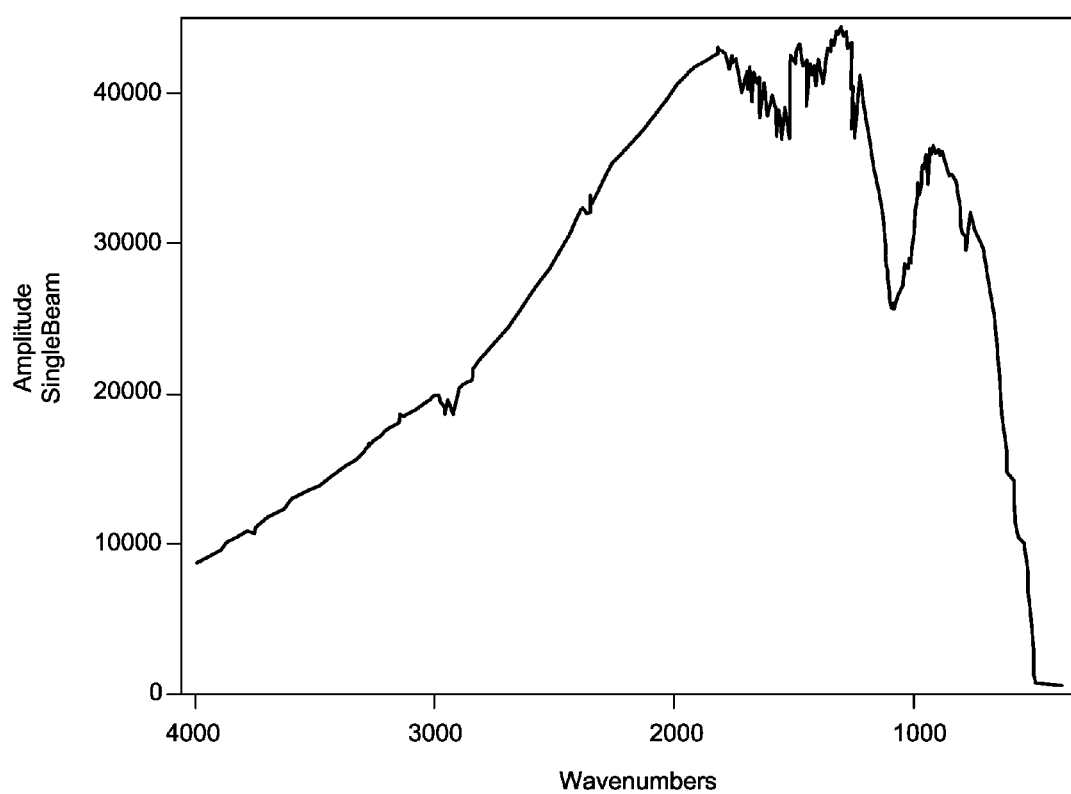
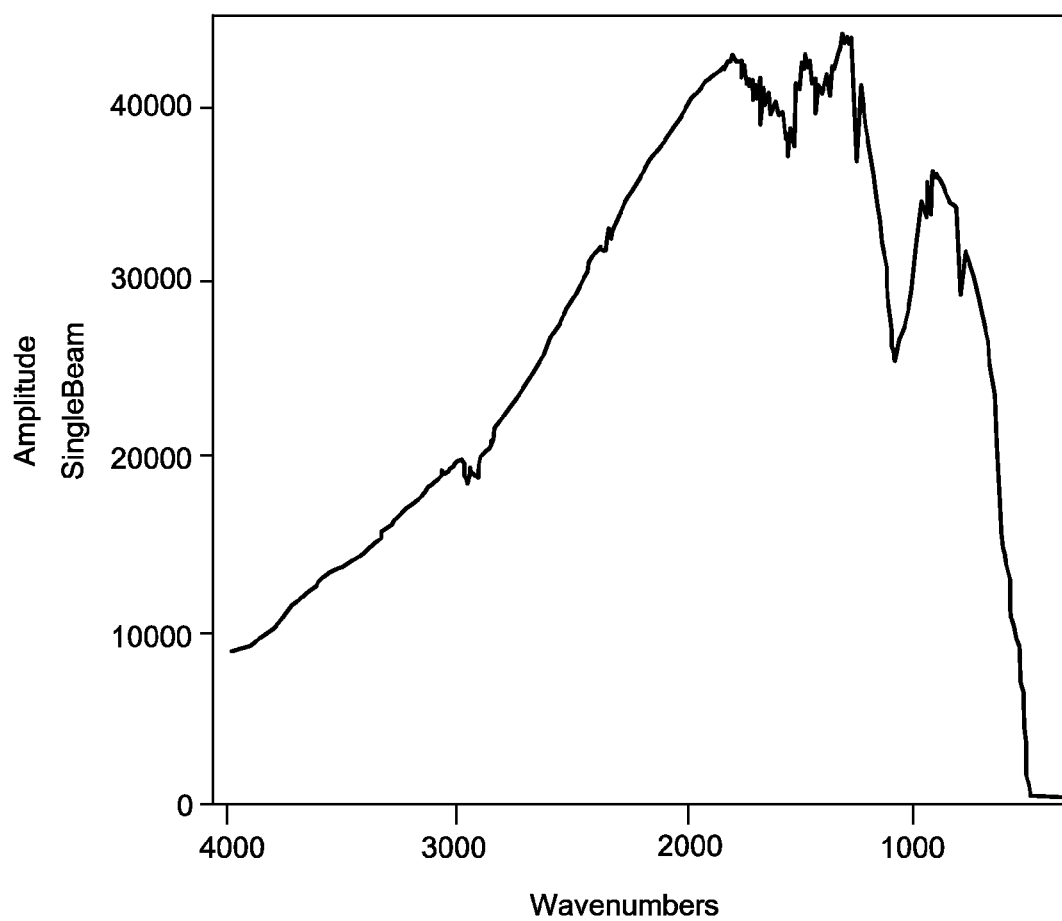


FIG. 4

**FIG. 5A**

***FIG. 5B***

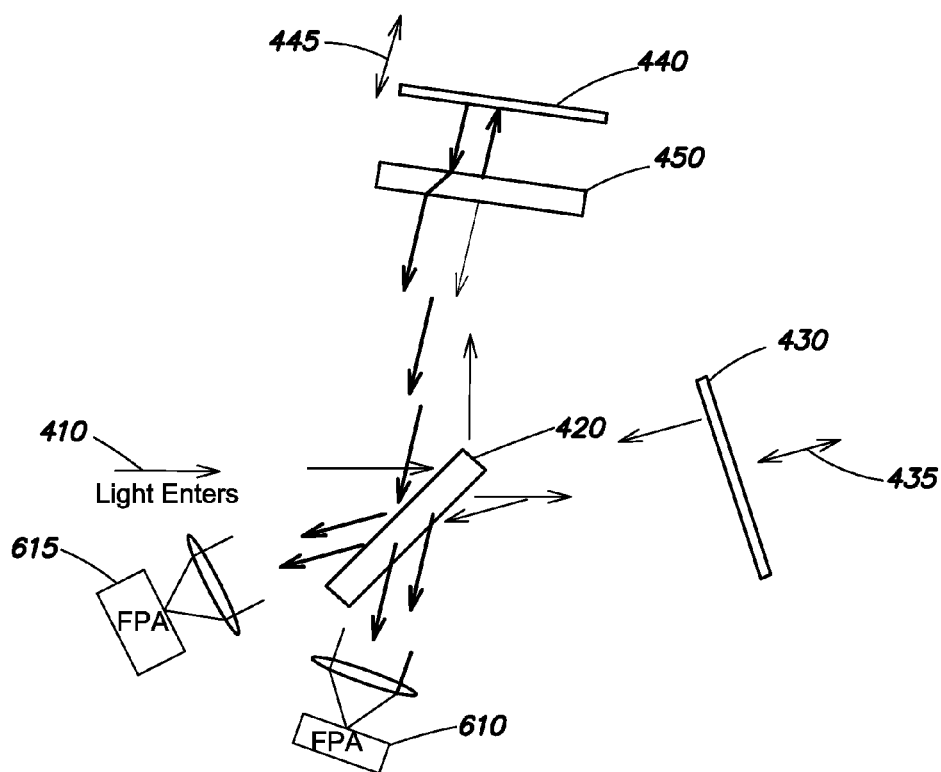


FIG. 6

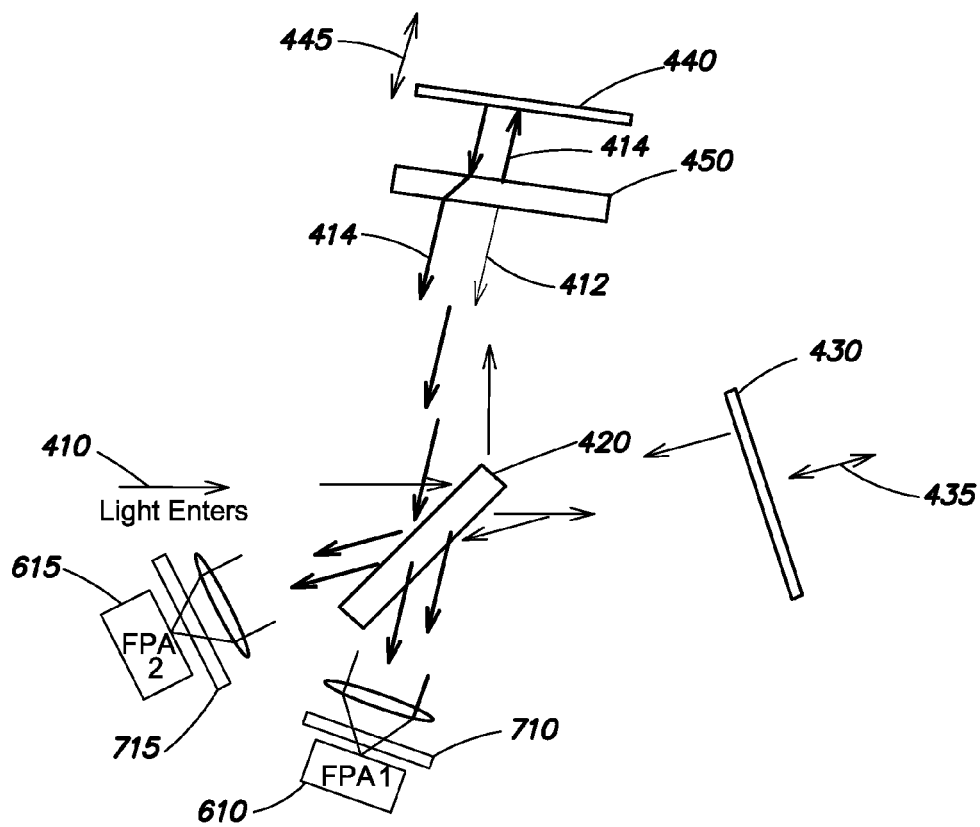


FIG. 7

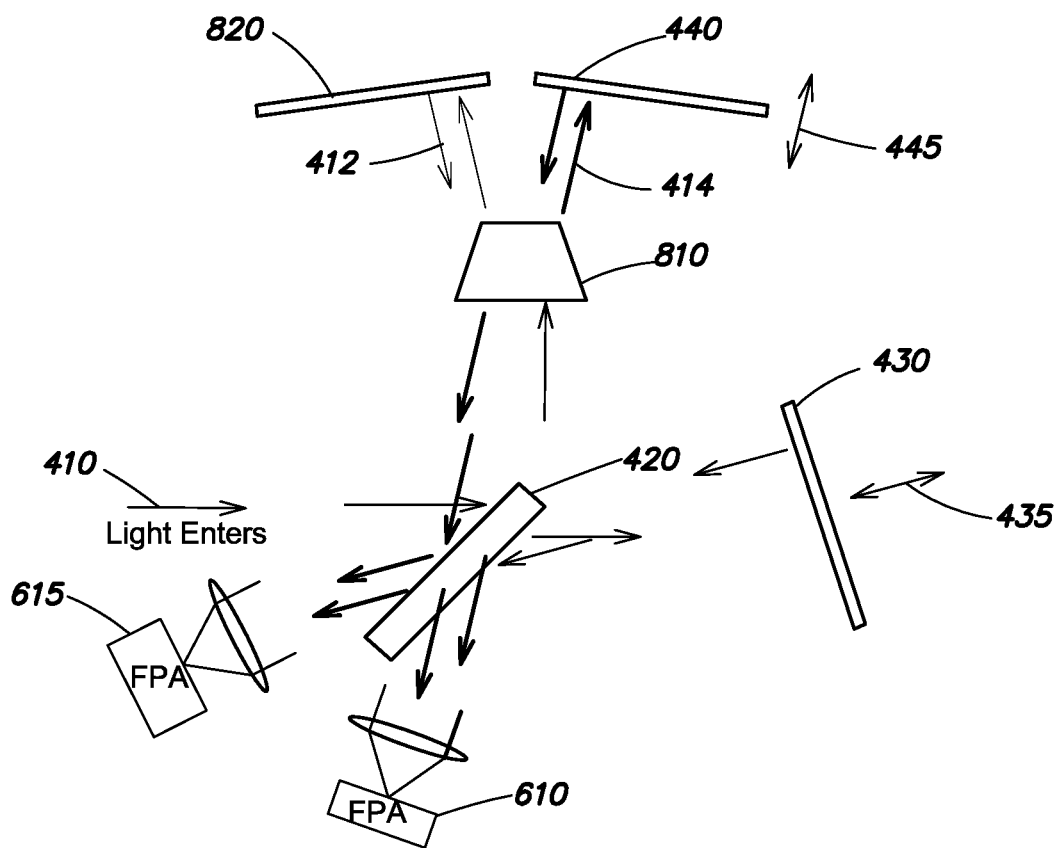


FIG. 8

CONFIGURABLE COMBINATION SPECTROMETER AND POLARIZER

BACKGROUND

Imaging spectroscopy is widely used in remote sensing applications. One type of interferometric spectrometer used to supply spectral data for many remote sensing applications is called a Fourier Transform Spectrometer (FTS). A common form of an FTS employs a Michelson interferometer with one arm having a variable optical path length. The variable optical path length may be implemented using a movable mirror. By scanning the movable mirror over some distance, an interference pattern or interferogram is produced that encodes the spectrum of the source. The FTS uses the Discrete Fourier Transform (DFT) or its faster algorithm, the Fast Fourier Transform (FFT), to convert the auto-correlation (each spectral amplitude encoded as the amplitude of a cosine signal) to physical spectra. The encoded spectrum is the Fourier transform of the source.

Referring to FIG. 1A, there is illustrated a block diagram of one example of an optical configuration of a conventional FTS using a scanning Michelson interferometer implemented with a movable mirror. In this example, the FTS includes two mirrors **105**, **110** with a beamsplitter **115** positioned between them. Mirror **105** is a fixed mirror and mirror **110** is a movable mirror. Electromagnetic radiation **120** incident on the beamsplitter **115** from a radiation source (not shown) is divided into two parts, each of which propagates down one of the two arms and is reflected off one of the mirrors. Radiation **120a** in a first optical path is reflected by the beamsplitter **115** and reflected by the fixed mirror **105**. On the return, the radiation **120a** is again split by the beamsplitter **115**, such that 50% of the radiation is reflected back to the input, and the remainder is transmitted through the beamsplitter to a focal plane array **125**. Radiation **120b** in a second optical path is transmitted through the beamsplitter **115**, and reflected by the movable mirror **110** which imparts a modulation to the radiation (motion of the mirror **110** is indicated by arrow **130**). On the return, the radiation **120b** is split by the beamsplitter **115** such that 50% of the radiation is transmitted through the beamsplitter back to the input, and the remainder is reflected to the focal plane array **125**. The two beams are recombined at the focal plane array **125**. When the position of the movable mirror **110** is varied along the axis of the corresponding arm (indicated by arrow **130**), an interference pattern, or interferogram, is swept out at the focal plane array **125** as the two phase-shifted beams interfere with each other.

FIG. 1B illustrates an alternative configuration of an FTS. In this configuration, two focal plane arrays **125a**, **125b** are used, and the fixed mirror **105** and moving mirror **110** are oriented such that approximately 50% of the radiation **120a**, **120b** from each optical path is directed to each focal plane array. The spectra from each focal plane array **125a**, **125b** may be averaged to improve the overall signal-to-noise ratio. This configuration avoids the 50% radiation loss associated with the configuration of FIG. 1A, but is more complex and requires additional components.

As discussed above, in the example FTS configuration of FIG. 1A, the focal plane array **125** receives a modulated interferogram; the modulation being caused by the motion of the movable mirror **110**. The focal plane array **125** converts the modulated interferogram to spectral information by measuring the amplitude of cosines at specific frequencies. In the configuration of FIG. 1B, each focal plane array **125a**, **125b** receives an identical modulated interferogram. The focal plane array(s) converts the modulated interferogram to spec-

tral information by measuring the amplitude of cosines at specific frequencies. FIG. 2 is a graph illustrating an example of the output from the focal plane array **125**. The amplitude of each measured frequency (f) is proportional to the amplitude of an incident wavenumber of radiation, v , according to $f=2vV$, where V is the velocity of the movable mirror **110**. This formula, hereinafter referred to as "Equation (1)," describes that for each incident wavenumber, there is a corresponding interferogram frequency for a given mirror velocity. The graph illustrated in FIG. 2 corresponds to the following example: an input waveband of approximately 8.3-14.3 micrometers (μm) (corresponding to an input wavenumber range of 1200-700 cm^{-1}); a mirror velocity, V , of 0.05 centimeters per second (cm/s), a two second scan, a scan resolution of approximately 10 cm^{-1} , and a sample rate of greater than 120 Hertz (Hz). For this example, Equation (1), $f=2vV$, yields a measured frequency range of approximately 35-60 Hz.

Polarimetry, or measurement of polarized electromagnetic radiation, may also provide useful information about an object, and typically provides at least some different information than is obtained by spectral imaging. In particular, polarimetry is sensitive to the object orientation, composition, and surface roughness, whereas, spectral information is primarily related to material composition. Therefore, in certain applications, it may be desirable to perform both spectral imaging and polarimetry.

Referring to FIG. 3, an FTS can be converted into a combined spectral imager and polarimeter (spectropolarimeter) by inserting a polarizer **310** into the optical path of the incident electromagnetic beam. Thus, polarized electromagnetic radiation **320** is provided to the FTS and analyzed as described above. The polarizer **310** may be switchable, such that the polarization of the incident electromagnetic radiation may be changed (e.g., from vertical or horizontal, or vice versa). With this arrangement, different polarizations are input, one at a time, to the FTS. Thus, the FTS measures one interferogram at a time (e.g., for either vertical or horizontal polarization). For the configuration illustrated in FIG. 3, the focal plane array **125** receives only $1/8^{\text{th}}$ of the original, unpolarized input radiation **120** because there is a 50% light loss due to transmission through the beamsplitter **115**, as discussed above, and the focal plane array **125** measures one polarization (with half the available signal) for half the total time (assuming both polarization measurements will be made). Thus, this arrangement is very inefficient in terms of photon collection efficiency and is susceptible to errors if the object or scene being measured undergoes changes while the inserted polarizer is switched. If the polarizer is not switched then the instrument only measures information in one polarization.

SUMMARY OF INVENTION

Aspects and embodiments are directed to a configurable combination imaging transform spectrometer and polarimeter that is capable of dynamically turning on and off the polarimetry function. Additionally, as discussed in more detail below, the polarimetry function is implemented "within" the spectrometer, rather than using a polarizing filter placed at the input to the system (as is sometimes done conventionally), thereby avoiding any additional signal loss at the system input.

According to one embodiment, a multimode configurable imaging spectropolarimeter comprises a first beamsplitter configured to split incident electromagnetic radiation from a scene into a first optical path and a second optical path, a movable first mirror positioned in the first optical path and

configured to reflect electromagnetic radiation in the first optical path, the first mirror being movable over a first scan range to provide a first optical path length difference between the first optical path and the second optical path, a polarizing beamsplitter positioned in the second optical path and configured to split electromagnetic radiation in the second optical path into a first polarization and a second polarization, the first and second polarizations being orthogonal to one another, a movable second mirror positioned in the second optical path and configured to reflect the first polarization, the movable second mirror being selectively movable over a second scan range to provide a second optical path length difference between the first and second polarizations, and at least one focal plane array sensor configured to receive electromagnetic radiation from the first and second optical paths and to produce a first interferogram corresponding to the first polarization and a second interferogram corresponding to the second polarization and superimposed on the first interferogram, with a frequency offset between the first and second superimposed interferograms.

In one example, the first interferogram comprises a first range of measured frequencies corresponding to one polarization and the second interferogram comprises a second range of measured frequencies corresponding to the second polarization, and wherein the frequency offset between the first and second ranges of frequencies is selected such that the first and second ranges of measured frequencies do not overlap. The first and second polarizations may be vertical polarization and horizontal polarization, for example. In one example, the at least one focal plane array sensor includes two focal plane arrays sensors each configured to receive the electromagnetic radiation from the first and second optical paths. The multimode configurable imaging spectropolarimeter may further comprise a first bandpass filter positioned in front of a first one of the two focal plane array sensors and having a first passband of wavelengths, and a second bandpass filter positioned in front of a second one of the two focal plane array sensors and having a second passband of wavelengths different from the first passband of wavelengths. The multimode configurable imaging spectropolarimeter may further comprise a fixed third mirror positioned in the second optical path, wherein the polarizing beamsplitter is configured to direct the first polarization to the movable second mirror and to direct the second polarization to the third mirror. In one example, the polarizing beamsplitter is configured to transmit the first polarization and to reflect the second polarization. The multimode configurable imaging spectropolarimeter may further comprise a controller configured to selectively interrupt a scanning movement of the movable first mirror and the movable second mirror, and to impart a vibration to one of the first and second mirrors so as to substantially prevent formation of the first and second interferograms at the at least one focal plane array sensor.

Another embodiment is directed to an imaging method comprising acts of receiving electromagnetic radiation from a scene with an imaging transform spectrometer, splitting the electromagnetic radiation into a first optical path and a second optical path within the imaging transform spectrometer, splitting electromagnetic radiation in the second optical path into first and second orthogonal polarizations, selectively producing first and second superimposed interferograms on a focal plane array sensor by selectively controlling movement of a movable first mirror in the first optical path to produce a first optical path length difference between the first and second optical paths, the first interferogram corresponding to the first polarization and the second interferogram corresponding to the second polarization, and selectively producing a frequency offset between the first and second superimposed interferograms by directing the first polarization to a movable second mirror, and selectively controlling movement of the movable second mirror in the second optical path to produce a second optical path length difference between the first and second polarizations.

In one example, the imaging method further comprises configuring the imaging transform spectrometer between a spectral imaging mode and a spectropolarimetric imaging mode by deactivating the movement of the movable first mirror to configure the imaging transform spectrometer into the spectral imaging mode, and activating the movement of the movable first mirror to configure the imaging transform spectrometer into the spectropolarimetric imaging mode. In another example, the imaging method further comprises configuring the imaging transform spectrometer into a broadband spatial imaging mode by deactivating the movement of the movable first mirror, deactivating the movement of the movable second mirror, and imparting a vibration to one of the first mirror and the second mirror to substantially prevent formation of the first and second interferograms at the at least one focal plane array sensor. In one example, splitting the electromagnetic radiation in the second optical path into the first and second orthogonal polarizations includes splitting the electromagnetic radiation in the second optical path into a vertical polarization component and a horizontal polarization component. In another example, splitting the electromagnetic radiation in the second optical path into the first and second orthogonal polarizations includes reflecting the second polarization from a polarizing beamsplitter, and transmitting the first polarization through the polarizing beamsplitter to the movable second mirror, wherein selectively producing the frequency offset further includes reflecting the first polarization with the movable second mirror. In another example, splitting the electromagnetic radiation in the second optical path into the first and second orthogonal polarizations includes directing the first polarization to the movable second mirror using a polarizing beamsplitter, directing the second polarization to a third fixed mirror, and reflecting the second polarization with the third fixed mirror. The first interferogram may comprise a first range of measured frequencies and the second interferogram may comprise a second range of measured frequencies. In this example, selectively producing the frequency offset includes producing a sufficient frequency offset such that the first and second ranges of measured frequencies do not overlap.

Still other aspects, embodiments, and advantages of these exemplary aspects and embodiments are discussed in detail below. Embodiments disclosed herein may be combined with other embodiments in any manner consistent with at least one of the principles disclosed herein, and references to “an embodiment,” “some embodiments,” “an alternate embodiment,” “various embodiments,” “one embodiment” or the like are not necessarily mutually exclusive and are intended to indicate that a particular feature, structure, or characteristic described may be included in at least one embodiment. The appearances of such terms herein are not necessarily all referring to the same embodiment.

Still other aspects, embodiments, and advantages of these exemplary aspects and embodiments are discussed in detail below. Embodiments disclosed herein may be combined with other embodiments in any manner consistent with at least one of the principles disclosed herein, and references to “an embodiment,” “some embodiments,” “an alternate embodiment,” “various embodiments,” “one embodiment” or the like are not necessarily mutually exclusive and are intended to indicate that a particular feature, structure, or characteristic described may be included in at least one embodiment. The appearances of such terms herein are not necessarily all referring to the same embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

Various aspects of at least one embodiment are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. The figures are included to provide illustration and a further understanding of the various aspects and embodiments, and are incorporated in and constitute a part of this specification, but are not intended as a

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definition of the limits of the invention. In the figures, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every figure. In the figures:

FIG. 1A is a block diagram of one example of a conventional interferometric spectrometer;

FIG. 1B is a block diagram of another example of a conventional interferometric spectrometer;

FIG. 2 is a graph of signal amplitude as a function of wavenumber, as may be obtained using an example of the interferometric spectrometer of FIG. 1A;

FIG. 3 is a block diagram of one example of an imaging transform spectrometer including a polarizer inserted in the input optical train;

FIG. 4 is a block diagram of one example of a configurable spectropolarimeter according to aspects of the invention;

FIG. 5A is a graph showing one example of an interferogram for the vertical polarization produced at the FPA sensor of the configurable spectropolarimeter of FIG. 4;

FIG. 5B is a graph showing one example of an interferogram for the horizontal polarization produced at the FPA sensor of the configurable spectropolarimeter of FIG. 4;

FIG. 6 is a block diagram of one example of a configurable dual-beam spectropolarimeter according to aspects of the invention;

FIG. 7 is a block diagram of another example of a configurable dual-beam spectropolarimeter according to aspects of the invention; and

FIG. 8 is a block diagram of another example of a configurable spectropolarimeter using two movable mirrors and a fixed mirror, according to aspects of the invention.

DETAILED DESCRIPTION

A sensor combining imaging spectrometry and polarimetry may provide powerful dual (orthogonal) phenomenologies to detect targets and reduce or eliminate false alarms. Conventional spectropolarimeters have low efficiency, and measure different polarizations sequentially or using separate focal plane arrays, which leads to spatial registration problems between the images measured in different polarizations. In addition, conventional spectropolarimeters suffer from issues with sensitivity and dividing the incoming signal into different wavebands and polarizations. Aspects and embodiments are directed to spectropolarimeters, based on imaging transform spectrometers, which are capable of providing “on demand” polarimetry featuring two simultaneous, perfectly registered polarization measurements. As discussed in more detail below, certain embodiments provide a method of modulating a mirror in the imaging transform spectrometer to “frequency shift” one polarization to a different set of frequencies, such that each polarization has a unique frequency band and both polarizations may be detected on a single focal plane array.

As discussed above, an imaging transform spectrometer, such as a Fourier transform spectrometer (FTS), uses a moving mirror to modulate an interferogram. In conventional Fourier transform spectrometers, Fourier analysis is used to covert this modulation into spectral information. Referring to FIGS. 1A and 1B, for unpolarized input light 120, the focal plane array(s) 125, or 125a, 125b, records two superimposed modulated interferograms; one of each of the two orthogonal polarization components (e.g., horizontal and vertical) of the input scene radiation, with coincident modulation frequencies for the respective polarizations. Conventionally there has not been a way to separate these superimposed modulated

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interferograms and the conventional analysis reports an amplitude value which is the sum of the two interferograms. According to certain embodiments, a unique modulation is imparted to one polarization, such that the one or more focal plane arrays receive two superimposed modulated interferograms, but where there is a frequency offset between all the frequencies of the spectra measured in the respective polarizations. In this manner, the interferograms may be separated, and the separate polarization measurements recovered in addition to the spectral information. As discussed in more detail below, both polarizations may be perfectly registered on each pixel of the focal plane array, and are measured simultaneously.

Aspects and embodiments disclosed herein may be applied to conventional Fourier transform spectrometers, or to other types of imaging spectrometers that use alternative methods (other than classic Fourier analysis) to convert the modulation into spectral information. For example, aspects and embodiments may be advantageously applied to the imaging spectrometer forms disclosed in commonly-owned U.S. Pat. No. 8,203,715 (hereinafter the ‘715 patent, and which is herein incorporated by reference in its entirety for all purposes) because the methods of retrieving spectral information disclosed in the ‘715 patent may be more robust to aliasing than classic Fourier analysis, and may therefore be particularly useful for recovering the distinct frequencies according to embodiments disclosed herein. Aspects and embodiments permit collection of spectropolarimetry using Michelson-type transform spectrometers, optionally with the use of uncooled bolometer focal plane arrays (for infrared measurements).

It is to be appreciated that embodiments of the methods and apparatuses discussed herein are not limited in application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. The methods and apparatuses are capable of implementation in other embodiments and of being practiced or of being carried out in various ways. Examples of specific implementations are provided herein for illustrative purposes only and are not intended to be limiting. Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use herein of “including,” “comprising,” “having,” “containing,” “involving,” and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. References to “or” may be construed as inclusive so that any terms described using “or” may indicate any of a single, more than one, and all of the described terms.

Referring to FIG. 4, there is illustrated a block diagram of one example of an imaging transform spectrometer configured to provide “on demand” polarimetry in accord with certain aspects and embodiments. Light 410, which may be essentially unpolarized, from an external scene enters the spectrometer and is split between two optical paths (two “arms” of the spectrometer) using a beamsplitter 420. Those skilled in the art will appreciate, given the benefit of this disclosure, that the polarization content of the light 410 does not affect aspects and embodiments of the present invention discussed below. The beamsplitter 420 is an optical element configured to allow part of an electromagnetic wave to pass through while reflecting the other part. As discussed above, one arm of the interferometer introduces a variable optical path length through movement of a first movable mirror 430. In one example, lateral movement of the movable mirror 430 along the axis of the corresponding arm, as shown by arrow 435, produces the optical path length difference. The movable

mirror scans over a range of movement along the axis indicated by arrow **435**, from an initial position to a furthest lateral extent, and back. The movable mirror **430** may be a corner cube, as illustrated in FIG. **4**, a plane mirror, or another reflecting device.

The other arm of the spectrometer includes a second mirror **440**, and a polarizing beamsplitter **450** that splits the light in that arm into two orthogonally polarized components. In following description, the two orthogonally polarized components will be referred to as vertical polarization and horizontal polarization; however, those skilled in the art will appreciate, given the benefit of this disclosure, that embodiments of the spectrometer may be alternatively configured to split the light into any two orthogonal components (e.g. left-hand and right-hand circularly polarized components.) In the illustrated example, the polarizing beamsplitter **450** is configured to reflect the horizontally polarized component **412** and pass the vertically polarized component **414**; however, in other embodiments, the opposite arrangement may be implemented. The vertically polarized component **414** is reflected from the second mirror **440**.

Light **416**, **418** returned from each arm is directed via the beamsplitter **420** to a focal plane array (FPA) sensor **460**, and the beams from each path are recombined at the FPA sensor. The result of the recombination is one or more interferograms produced at the FPA sensor **460**. The FPA sensor **460** may include a set of photo-detector elements and corresponding electronics arranged at or near the focus of the interference pattern. For example, the set of photo-detectors elements can be arranged as a linear array or in a two-dimensional matrix.

According to one embodiment, an actuating mechanism, such as a piezoelectric transducer, for example, is coupled to the second mirror **440** and configured to move the second mirror along the axis of its corresponding arm of the spectrometer, as shown by arrow **445**. This movement of the second mirror **440** introduces a variable and controllable optical path length difference between the vertical and horizontal polarized components **412**, **414** of the light, and also changes the velocity component, V , of Equation (1) for the transmitted component (in the illustrated example, the vertically polarized component **414**). The effective mirror velocity for the vertically polarized component **418** is the sum of the two mirror velocities. Thus, given a velocity V_1 of the movable mirror **430**, and a velocity V_2 of the second mirror **440**, the frequency bands of interferograms produced at the FPA sensor **460** for the two orthogonal polarizations **416**, **418** are given by:

$$f_H = 2\nu V_1 \quad (2)$$

$$f_V = 2\nu(V_1 + V_2) \quad (3)$$

where f_H is the frequency band of the interferogram produced for the horizontally polarized component of the light **416** received at the FPA sensor **460**, and f_V is the frequency band of the interferogram produced for the vertically polarized component of the light **418**.

For example, consider an input waveband of approximately 8.5-14.3 μm (corresponding to an input wavenumber range of 1200-700 cm^{-1}); $V_1 = 0.05 \text{ cm/s}$; $V_2 = 0.05 \text{ cm}^{-1}/\text{s}$; a two second scan, a scan resolution of approximately 10 cm^{-1} , and a sample rate of greater than 240 Hz. For this example, Equation (2) yields a measured frequency range of approximately 60-35 Hz for the horizontally polarized component, and Equation (3) yields a measured frequency range of approximately 120-70 Hz for the vertically polarized component. FIGS. **5A** and **5B** illustrate interferograms which may be produced at the FPA sensor **460** for this example. FIG. **5A**

illustrates an example of the interferogram for the vertical polarization, where the wavenumber range corresponds to a measured frequency range of approximately 120-70 Hz, as discussed above. FIG. **5B** illustrates an example of the interferogram for the horizontal polarization, where the wavenumber range corresponds to a measured frequency range of approximately 60-35 Hz, as discussed above.

Thus, the FPA sensor **460** receives two superimposed modulated interferograms where each interferogram is in a unique frequency band; one for the horizontal polarization and one for the vertical polarization. Because the effective mirror velocity is altered only for the vertical polarization (in this case) by the movement of the second mirror **440**, the measured frequency ranges for the two polarizations are offset. By controlling the velocity of movement, V_2 , of the second mirror **440**, the amount of frequency offset may be controlled. Thus, by setting V_2 to zero, the system may act as a spectral imager (imaging transform spectrometer) only, as the two interferograms (for the two polarizations) produced at the FPA sensor **460** are superimposed having identical frequency bands, as discussed above. By setting V_2 to a predetermined value, the system may be dynamically configured to collect spectropolarimetry "on demand."

As discussed above, an alternative arrangement of an imaging transform spectrometer includes a pair of FPA sensors that each receives the light from the beamsplitter and produces a corresponding interferogram, as shown in FIG. **1B**. Aspects and embodiments may be applied to this type of imaging transform spectrometer to convert the spectral imager into an "on demand" spectropolarimeter, as discussed above. For example, referring to FIG. **6**, there is illustrated an example of a configurable spectropolarimeter including two FPA sensors **610**, **615**, according to one embodiment. Each FPA sensor **610**, **615** receives two superimposed modulated interferograms; one for the vertical polarization and one for the horizontal polarization, as discussed above. The difference compared to the embodiment discussed above with reference to FIG. **4**, is that instead of light being lost through the beamsplitter **420**, out along the input path, the returned light is shared between the two FPA sensors **610**, **615**. In one example, interleaved sampling between the two FPA sensors **610**, **615** may be used to increase the effective sampling rate, as described, for example, in commonly-owned US PG-Pub. No. 2013/0277560, which is herein incorporated by reference in its entirety for all purposes. As with the example described above with reference to FIG. **4**, by setting the velocity V_2 of motion of the second mirror **440** to zero, the polarimetry function may be turned off, returning operation of the system to that of a spectral imager alone.

According to another embodiment, bandpass filtering of the scene spectrum may be used to decrease the velocity V_2 of motion of the second mirror **440**, which may be advantageous or desirable in certain applications. For example, referring to FIG. **7**, there is illustrated one example of a configurable spectropolarimeter implementing bandpass filtering according to one embodiment. In the illustrated example, a first bandpass filter **710**, configured to pass a first range of wavelengths, is positioned in front of the first FPA sensor **610**, and a second bandpass filter **715**, configured to pass a second range of wavelengths, is positioned in front of the second FPA sensor **615**. Splitting the colors (range of frequencies) received by each FPA sensor **610**, **615** reduces the bandwidth used by each sensor, and accordingly, allows the velocity V_2 of motion of the second mirror **440** to be reduced because the velocity V_2 is proportional to the bandwidth (as shown by Equations (1)-(3)). The frequency band received by each FPA sensor **610**, **615**, and therefore the wavelength passband of the

corresponding bandpass filter **710**, **715**, may be set independently and optimized for a desired sample rate.

For example, consider an input waveband (for light **410**) of approximately 7.7-14.3 μm (corresponding to an input wavenumber range of approximately 1200-700 cm^{-1}); $V_1=0.05$ cm/s ; a two second scan, and a scan resolution of approximately 10 cm^{-1} . Using bandpass filtering, V_2 may be reduced to 0.02 cm^{-1}/s from 0.05 cm^{-1}/s in the example discussed above. For this example, Equation (2) yields a measured frequency range of approximately 60-35 Hz for the horizontally polarized component, and Equation (3) yields a measured frequency range of approximately 84-52.5 Hz for the vertically polarized component.

In one example, the passband for the first bandpass filter **710** may be selected such that the first FPA sensor **610** receives wavenumbers in the range of approximately 940-1200 cm^{-1} , and the passband for the second bandpass filter **715** may be selected such that the second FPA sensor **615** receives wavenumbers in the range of approximately 700-960 cm^{-1} . Thus, the first FPA sensor **610** may produce an interferogram for the horizontal polarization over a measured frequency range of approximately 47-60 Hz, and an interferogram for the vertical polarization over a measured frequency range of approximately 66-84 Hz. Similarly, the second FPA sensor **615** may produce an interferogram for the horizontal polarization over a measured frequency range of approximately 35-48 Hz, and an interferogram for the vertical polarization over a measured frequency range of approximately 49-67 Hz. Thus, in this example, the total bandwidth of signals on the first FPA sensor **610** is approximately 37 Hz, and the total bandwidth of signals on the second FPA sensor **615** is approximately 32.2 Hz. The frequencies may be extracted from each FPA sensor **610**, **615** to reconstruct a composite interferogram for each polarization component, and produce the polarimetry data. In this example, the sampling rate may be reduced to approximately 168 Hz, compared to the 240 Hz sampling rate used in the above-discussed example.

In another embodiment, interleaved sampling may be used, as discussed above. For example, for the above-noted example bandwidths, a sampling rate of 84 Hz may be used for the first FPA sensor **610**, and a sampling rate of 67 Hz may be used for the second FPA sensor **615**.

In another embodiment, the sampling rate may be the same for both FPA sensors. The sampling rate, F_s , may be selected according to the following "bandpass sampling" equations:

$$\frac{2f_H}{k} \leq F_s \leq \frac{2(f_H - B)}{k-1} \quad (4)$$

$$k \leq \frac{f_H}{B} \quad (5)$$

In Equations (4) and (5), k is any integer that satisfies Equation (5), and B is the bandwidth. Similar equations may constrain F_s for f_v . Those skilled in the art will appreciate, given the benefit of this disclosure, that bandpass sampling is separate and independent from the bandpass filtering of the spectrum discussed above; however, in practice it may be easier to apply bandpass sampling when the bandwidth of the signal to be sampled is narrowed by using bandpass filtering.

In embodiments discussed above with reference to FIG. 4, the polarizing beamsplitter **450** is configured to reflect the horizontally polarized component **412** and pass the vertically polarized component **414**. Referring to FIG. 8, according to another embodiment, the polarizing beam splitter **450** may be replaced with an achromatic polarizing beamsplitter, or Wol-

laston prism, **810** that passes both polarizations, but directs the two components in slightly different directions. Thus, the vertical polarization **414** may be directed to the second mirror **440** and the horizontal polarization **412** may be directed to a third mirror **820**, for example. Both polarizations are reflected from the respective mirrors **440**, **820**, and returned via the achromatic polarizing beamsplitter **810** and beamsplitter **420** to the FPA sensors **610**, **615** and processed as discussed above. The third mirror **820** may be a fixed mirror. Motion of the second mirror **440** (indicated by arrow **445**) may introduce an optical path length difference between the vertical and horizontal polarizations **414**, **412**, thus producing offset frequency ranges in the interferograms of the two polarizations, as discussed above.

Thus, aspects and embodiments provide a configurable spectropolarimeter wherein controlled movement of the second mirror **440** may be selectively activated, to allow the system to collect polarimetry as discussed above, and deactivated to return the system to a spectral imaging mode in which polarimetry is not collected. Dual polarization imagery may be collected on a single FPA sensor. The two polarizations are perfectly registered on each pixel of the sensor, and are collected simultaneously. In certain embodiments, bandpass filtering and/or bandpass sampling may be used, as discussed above. Additionally, in dual-beam configurations with bandpass filtering, bandpass sampling may be used to transition the signals closer to baseband and reduce sampling speed requirements, as well as to allow the same sampling rate to be used for both FPA sensors.

Furthermore, according to certain embodiments, a configurable spectropolarimeter as discussed above may be further configured to implement a camera, or broadband spatial imaging mode. Commonly-owned, co-pending U.S. application Ser. No. 14/166,067, titled "CONFIGURABLE COMBINATION SPECTROMETER AND IMAGER," filed on Jan. 28, 2014, which is herein incorporated by reference in its entirety, describes techniques by which an imaging transform spectrometer may be configured, on demand, into either a spectral imaging mode or a camera mode through purposeful, selective destruction of the interference pattern used for spectral imaging. This may be achieved by selectively halting the scanning motion of the first movable mirror **430**, physically modulating one of the two mirrors **430**, **440** to destroy the interferogram. Specifically, actuator (such as a piezoelectric transducer, for example) may be coupled to either the first mirror **430** or second mirror **440**, and configured to cause the mirror to vibrate rapidly back and forth along the direction of the axis of the respective arm of the interferometer (represented by arrows **435** and **445**, respectively), with a small amplitude motion. This vibration causes a frequency shift to the modulation for the radiation striking the mirror **430** or **440**, and substantially destroys the interference pattern. Accordingly, the resulting image obtained by the FPA sensor is a broadband image of the scene without modulation. Spectral collection may be interrupted, on demand or at any time, to collect broadband unmodulated images. Thus, according to certain embodiments, an imaging transform spectrometer may be dynamically configured between a spectral imaging mode, a spectropolarimetry mode, and a broadband imaging mode, by controlling the movement of mirrors **430** and **440**. In this manner, a highly flexible instrument may be provided, which is capable of being rapidly reconfigured to obtain different types of images and different information from a viewed scene.

Having described above several aspects of at least one embodiment, it is to be appreciated various alterations, modifications, and improvements will readily occur to those

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skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure and are intended to be within the scope of the invention. Accordingly, the foregoing description and drawings are by way of example only, and the scope of the invention should be determined from proper construction of the appended claims, and their equivalents.

What is claimed is:

1. A multimode configurable imaging spectropolarimeter comprising:

- a first beamsplitter configured to split incident electromagnetic radiation from a scene into a first optical path and a second optical path and to direct reflected electromagnetic radiation from the first and second optical paths along a combined optical path toward a focal plane;
- a movable first mirror positioned in the first optical path and configured to reflect electromagnetic radiation in the first optical path back toward the first beamsplitter, the first mirror being movable over a first scan range to provide a first optical path length difference between the first optical path and the second optical path;
- a polarizing beamsplitter positioned in the second optical path and configured to split electromagnetic radiation in the second optical path into a first polarization and a second polarization, the first and second polarizations being orthogonal to one another;
- a movable second mirror positioned in the second optical path and configured to reflect the first polarization toward the first beamsplitter, the second mirror being selectively movable over a second scan range to provide a second optical path length difference between the first and second polarizations;
- a fixed third mirror positioned in the second optical path and configured to reflect the second polarization toward the first beamsplitter; and
- at least one imaging sensor positioned at the focal plane and configured to receive the reflected electromagnetic radiation from the first and second optical paths and to produce a first interferogram from interference between the first polarization and the reflected electromagnetic radiation from the first optical path and a second interferogram from interference between the second polarization and the reflected electromagnetic radiation from the first optical path, the second interferogram being superimposed on the first interferogram and offset in frequency relative to the first interferogram.

2. The multimode configurable imaging spectropolarimeter of claim 1, wherein the first interferogram comprises a first range of measured frequencies corresponding to the first polarization and the second interferogram comprises a second range of measured frequencies corresponding to the second polarization, and wherein the first and second ranges of measured frequencies do not overlap.

3. The multimode configurable imaging spectropolarimeter of claim 2, wherein the at least one imaging sensor includes two imaging sensors each configured to receive the reflected electromagnetic radiation from the first and second optical paths.

4. The multimode configurable imaging spectropolarimeter of claim 3, further comprising:

- a first bandpass filter positioned in front of a first one of the two imaging sensors and having a first passband including the first range of measured frequencies; and
- a second bandpass filter positioned in front of a second one of the two imaging sensors and having a second passband including the second range of measured frequencies.

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5. The multimode configurable imaging spectropolarimeter of claim 1, wherein the first and second polarizations are vertical polarization and horizontal polarization.

6. The multimode configurable imaging spectropolarimeter of claim 1, further comprising a controller configured to selectively interrupt a scanning movement of the first mirror and the second mirror, and to impart a vibration to one of the first and second mirrors so as to substantially prevent formation of the first and second interferograms at the at least one imaging sensor.

7. An imaging method comprising:

- receiving electromagnetic radiation from a scene with an imaging transform spectrometer;
- splitting the electromagnetic radiation into a first optical path and a second optical path within the imaging transform spectrometer;
- splitting electromagnetic radiation in the second optical path into first and second orthogonal polarizations;
- reflecting the first and second polarizations and electromagnetic radiation from the first optical path to a focal plane;
- selectively producing first and second superimposed interferograms on an imaging sensor positioned at the focal plane by selectively controlling movement of a movable first mirror in the first optical path to produce a first optical path length difference between the first and second optical paths, the first interferogram produced from interference between the first polarization and the electromagnetic radiation reflected from the first optical path, and the second interferogram produced from interference between the second polarization and the electromagnetic radiation reflected from the first optical path;
- selectively producing an offset in frequency between the first and second superimposed interferograms by directing the first polarization to a movable second mirror, and selectively controlling movement of the second mirror in the second optical path to produce a second optical path length difference between the first and second polarizations; and
- configuring the imaging transform spectrometer between a spectral imaging mode and a spectropolarimetric imaging mode by deactivating the movement of the movable first mirror to configure the imaging transform spectrometer into the spectral imaging mode, and activating the movement of the movable first mirror to configure the imaging transform spectrometer into the spectropolarimetric imaging mode.

8. The imaging method of claim 7, further comprising:

- configuring the imaging transform spectrometer into a broadband spatial imaging mode by:
- deactivating the movement of the movable first mirror;
- deactivating the movement of the movable second mirror; and
- imparting a vibration to one of the movable first mirror and the movable second mirror to substantially prevent formation of the first and second interferograms at the at least one imaging sensor.

9. The imaging method of claim 7, wherein splitting the electromagnetic radiation in the second optical path into the first and second orthogonal polarizations includes splitting the electromagnetic radiation in the second optical path into a vertical polarization component and a horizontal polarization component.

10. The imaging method of claim 7, wherein splitting the electromagnetic radiation in the second optical path into the first and second orthogonal polarizations includes:

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reflecting the second polarization from a polarizing beam-splitter; and
 transmitting the first polarization through the polarizing beam-splitter to the movable second mirror; and
 wherein selectively producing the offset in frequency further includes reflecting the first polarization with the movable second mirror.

11. The imaging method of claim 7, wherein splitting the electromagnetic radiation in the second optical path into the first and second orthogonal polarizations includes:

directing the first polarization to the movable second mirror using a polarizing beamsplitter;
 directing the second polarization to a fixed third mirror;
 and
 reflecting the second polarization with the fixed third mirror.

12. The imaging method of claim 7, wherein the first interferogram comprises a first range of measured frequencies and the second interferogram comprises a second range of measured frequencies, and wherein selectively producing the offset in frequency includes producing a sufficient offset in frequency such that the first and second ranges of measured frequencies do not overlap.

13. A multimode configurable imaging spectropolarimeter comprising:

a first beamsplitter configured to split incident electromagnetic radiation from a scene into a first optical path and a second optical path and to direct reflected electromagnetic radiation from the first and second optical paths along a combined optical path toward a focal plane;

a movable first mirror positioned in the first optical path and configured to reflect electromagnetic radiation in the first optical path back toward the first beamsplitter, the first mirror being movable over a first scan range to provide a first optical path length difference between the first optical path and the second optical path;

a polarizing beamsplitter positioned in the second optical path and configured to split electromagnetic radiation in the second optical path into a first polarization and a second polarization, the first and second polarizations being orthogonal to one another, the polarizing beamsplitter being further configured to transmit the first polarization and to reflect the second polarization toward the first beamsplitter;

a movable second mirror positioned in the second optical path and configured to reflect the first polarization

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toward the first beamsplitter, the second mirror being selectively movable over a second scan range to provide a second optical path length difference between the first and second polarizations;

at least one imaging sensor positioned at the focal plane and configured to receive the reflected electromagnetic radiation from the first and second optical paths and to produce a first interferogram from interference between the first polarization and the reflected electromagnetic radiation from the first optical path and a second interferogram from interference between the second polarization and the reflected electromagnetic radiation from the first optical path, the second interferogram being superimposed on the first interferogram and offset in frequency relative to the first interferogram; and
 a controller configured to selectively interrupt a scanning movement of the first mirror and the second mirror, and to impart a vibration to one of the first and second mirrors so as to substantially prevent formation of the first and second interferograms at the at least one imaging sensor.

14. The multimode configurable imaging spectropolarimeter of claim 13, wherein the first and second polarizations are vertical polarization and horizontal polarization.

15. The multimode configurable imaging spectropolarimeter of claim 13, wherein the first interferogram comprises a first range of measured frequencies corresponding to the first polarization and the second interferogram comprises a second range of measured frequencies corresponding to the second polarization, and wherein the first and second ranges of measured frequencies do not overlap.

16. The multimode configurable imaging spectropolarimeter of claim 15, wherein the at least one imaging sensor includes two imaging sensors each configured to receive the reflected electromagnetic radiation from the first and second optical paths.

17. The multimode configurable imaging spectropolarimeter of claim 16, further comprising:

a first bandpass filter positioned in front of a first one of the two imaging sensors and having a first passband including the first range of measured frequencies; and

a second bandpass filter positioned in front of a second one of the two imaging sensors and having a second passband including the second range of measured frequencies.

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